Bursts of star formation and gas outflows in galaxies

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Outline

1. Star formation and starburst galaxies
2. Superwinds and galaxy evolution
3. Case study
   • Observations of the galaxy M82
Star formation in galaxies

- Star formation occurs in molecular clouds (e.g., Kennicutt 1998, Kennicutt et al. 2007; Krumholz et al. 2011)
- Observations of molecular gas → understand star formation → key to galaxy evolution

Spiral galaxy M51 (Credit: HST)
Baryon flow in a typical disk galaxy

Mass budget in our Galaxy:

- Dark matter
- Baryons (~10%) = visible matter
  ~90% of baryons in stars, ~10% in interstellar medium (ISM)
  (gas, dust grains, PAHs, cosmic rays)

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ISM
~7 x 10^9 M_{sun}
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Star formation rate
~1.3 M_{sun}/yr

Star formation sustainable over ~10^9 yr

Supernova explosions, stellar winds, etc.
~0.5 M_{sun}/yr

Stars
Star formation feedback in starburst galaxies

Starburst galaxies
Star formation rate $\sim 10-100 \, M_{\text{sun}}/\text{yr}$
$\rightarrow$ molecular gas consumed at furious rate

ISM

Superwind
Outflow of gas and dust

Feeding
Star formation rate

Feedback
Radiation, supernova rate

Cleg & Chevalier (1985)
Schiano (1985)
Heckman et al. (1990)
Strickland et al. (2004)
Murray et al. (2005, 2011)
Veilleux et al. (2005)
Fabian (2012)
Krumholz & Thompson (2013)
...
Superwinds and galaxy evolution

Interaction/merging of gas-rich galaxies → Starburst (high star formation rate) → Superwind

 Suppress star formation

Transport heavy elements ($Z>2$) to intergalactic space

M82 (Credit: Chandra, HST)

Arp 220 (Credit: HST)
Multi-phase outflows: M82 case study

Mutchler et al. (2007)

Starburst nucleus

Highly inclined stellar disk

Optical (B-band)

1 kpc

Mutchler et al. (2007)

Outflow

Optical (H-alpha line)

Kilgard et al.

Outflow

X-ray (0.7-1.1 keV)

Kaneda et al. (2010)

Outflow

Infrared (PAH molecules)
Observations of molecular gas

How is molecular gas affected by the superwind?
Interstellar molecular gas is cooled by CO (J=1→0) λ=2.6 mm (J : rotational quantum number)

Nobeyama Radio Observatory
45-m telescope

Combined Array for Research in mm-wave Astronomy (CARMA)

Antenna diameter = 45m → high sensitivity
Array of 6-m and 10-m antennas → high angular resolution
Molecular gas outflow

Observations with Nobeyama 45-m telescope

- Large-scale molecular gas outflow >2 kpc above the galactic plane (1 pc = $3.1 \times 10^{13}$ km)
High-resolution CO observations

CARMA + Nobeyama 45m map
highest-resolution CO map (CANON project)
(2.8 x 2.5 arcsec$^2$ equivalent to ~45 pc)
Close-up of the molecular gas outflow

Molecular gas outflows launched from the 300-pc ring

→ How does the superwind affect star formation?
→ Can molecular gas escape?

- Outflow velocity from CO spectra
- $H_2$ gas mass from CO line flux
- Mass outflow rate
CO (J=1-0) intensity

Mean outflow velocity
~100 km/s

molecular gas ring inclined 80°
Superwind and the evolution of ISM in M82

Molecular gas outflow:

Mean velocity 100 km/s < escape velocity (~300 km/s)

Mass outflow rate 30 $M_{\odot}$/yr $\geq$ star formation rate (~10 $M_{\odot}$/yr)

(e.g. Förster Schreiber et al. 2003)

Momentum rate $3 \times 10^3$ $M_{\odot}$/yr km/s $\sim$ starburst input

(radiation pressure, supernovae)

$\Rightarrow$ Molecular gas blown out within $< 10^7$ yr

$\Rightarrow$ Strong suppression of star formation
Conclusions

• Star formation in starburst galaxies triggers the superwind feedback

• Superwinds play essential role in galaxy evolution

• Observations of M82 show outflow of hot and cold gas
  • Molecular gas will be depleted within $<10^7$ Myr
  • Star formation will be suppressed by the superwind

• Observations of galactic superwinds with new instruments (e.g., ALMA in Chile) are promising to probe starburst feedback across cosmic history

Thank you!